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Plume Diffusion in a Residential Neighborhood during Stable Conditions

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PLUME DIFFUSION IN A RESIDENTIAL NEIGHBORHOOD DURING STABLE CONDITIONS

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16. ABSTRACT

The EPA Integrated Air Cancer Program (IACP) is a comprehensive, multidisciplinary effort to study woodsmoke emissions, woodsmoke transport, chemistry, and ultimately health effects in residential neighborhoods. As part of this work, an extensive field study was conducted in Boise, Idaho during the winter 1986-1987. During this study, a series of atmospheric tracer releases was conducted. The purpose of these tracer tests was to investigate plume dispersion under wintertime, nighttime conditions in an urban valley as a basis for determining the relative impact of nearby and far away sources upon air quality monitoring sites.

Previously, a preliminary tracer study, conducted on a neighborhood scale in Pullman, Washington, showed that enhanced plume diffusion occurred for plumes released from residential chimneys during stable drainage winds (Ferrara and Lamb, 1986). In this study, hourly averaged diffusion rates exceeded typical rural diffusion rates by more than two stability classes and the McElroy-Pooler urban diffusion curves by one stability class. Horizontal diffusion rates estimated from turbulence data measured at the source agreed within 38% of the observed diffusion rates over distances of less than 1 km.

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1. INTRODUCTION

The EPA Integrated Air Cancer Program (IACP) is a comprehensive, multidisciplinary effort to study woodsmoke emissions, woodsmoke transport, chemistry, and ultimately health effects in residential neighborhoods. As part of this work, an extensive field study was conducted in Boise, ID during the winter, 1986-87. During this study, a series of atmospheric tracer releases was conducted. The purpose of these tracer tests was to investigate plume dispersion under wintertime, nighttime conditions in an urban valley as a basis for determining the relative impact of nearby and far away sources upon air quality monitoring sites.

Previously, a preliminary tracer study, conducted on a neighborhood scale in Pullman, WA showed that enhanced plume diffusion occurred for plumes released from residential chimneys during stable drainage winds (Ferrara and Lamb, 1986). In this study, hourly averaged diffusion rates exceeded typical rural diffusion rates by more than two stability classes and the McElroy-Pooler urban diffusion curves by one stability class. Horizontal diffusion rates estimated from turbulence data measured at the source agreed within 38% of the observed diffusion rates over distances of less than 1 km.

2. EXPERIMENTAL PROCEDURES

The test area was a residential neighborhood on the north edge of Boise approximately 5 km from the downtown business district. Boise lies in the Boise River valley which drains from the southeast. The test neighborhood lies at the foot of a relatively steep and high mountain range bordering the valley. A major tributary exits into the valley at the northeast corner of the neighborhood. During wintertime nights, drainage flow down the valley produces light southeast winds. These winds are perturbed by drainage from the tributary to yield more easterly winds across the neighborhood. The houses in the neighborhood are typically older one story structures. Many of the houses have fireplaces or woodstoves. There are numerous large deciduous trees and extensive shrubbery and landscaping throughout the area.

The primary air quality sampling site in the EPA study was located in a park near the center of the neighborhood. We selected four houses located from less than 100 m to 800 m from the park for tracer release points. During the normal neighborhood tests, SF_6 was released from house 1, $CBrF_3$ was released from house 2, F-114 was released from house 3, and F-22 was released from house 4. In each case, tracer was released through a calibrated rotameter and tubing inserted down into the chimney or wood stove pipe. Tracers were released at a steady rate beginning approximately 10 min prior to the sampling period.

Approximately 40 sequential syringe samplers and 20 sequential bag samplers were used to collect hourly averaged air samples during each test. While the sampling array changed from test to test, the overall design placed a line of samplers downwind of each source and one or more longer lines downwind of the entire source domain.

A continuous fast-response SF_6 analyzer was operated at the primary meteorological tower in the park in conjunction with a sonic anemometer at 10 m. A second continuous analyzer was operated in a van driven along traverses at various distances downwind of the tracer source. Data from the stationary analyzer was recorded at 10 Hz, while data from the mobile system was recorded at 1 Hz.

The primary meteorological system was a 30 m tower in the park instrumented at 10 and 30 m with a pair of 3 dimensional sonic anemometers (Applied Technology, Inc.), a pair of Gill bivane anemometers, and a pair of aspirated temperature sensors for delta-temperature measurements. Additional vertical profile data were collected periodically during each tracer test using a portable tethersonde operated in an open school yard approximately 1 km west of the test neighborhood. A number of other surface wind stations were operated as part of the general health effects study throughout the Boise valley.

3. RESULTS AND DISCUSSION

Six tracer tests were conducted during December, 1986, and approximately 19 hours of multiple tracer data were collected. The test periods and average meteorological conditions during each test are summarized in Table 1. In general, drainage winds during the night produced light flow from east to west across the neighborhood with relatively strong surface temperature inversions extending up to 100 m by late evening as shown in Figure 1. The depth of the drainage flow varied, but in some cases reached 100 m or more when the drainage and synoptic winds were approximately parallel. In some cases, however, there appeared to be a balance between opposing synoptic and drainage

Table 1. Summary of Meteorological Conditions

Test	Start Time	$\bar{u}$ ms^{-1}	$\overline{WD}$ deg	σ_v ms^{-1}	σ_w ms^{-1}
1	1900	-	80	0.17	0.07
	2000	-	107	0.31	0.07
	2100	-	309	0.23	0.07
2	1900	0.48	106	0.10	0.03
	2000	0.59	96	0.12	0.02
	2100	0.41	79	0.10	0.03
	2200	0.55	94	0.11	0.02
3	2030	0.50	102	0.30	0.06
	2130	0.80	106	0.25	0.05
4	2400	0.42	162	0.25	0.09
	0100	0.37	62	0.21	0.06
5	1900	0.36	30	0.40	0.10
	2000	1.01	313	0.42	0.71
	2100	1.26	317	0.55	0.33
	2200	0.32	1	0.65	1.18
6	2000	0.88	95	0.38	0.19
	2100	0.78	93	0.36	0.20
	2200	0.99	95	0.39	0.31
	2300	0.86	85	0.35	0.15

winds and air flow over the neighborhood became very light and variable.

Tests 1,2, 4, and 5 were neighborhood scale experiments where tracers were released from the designated houses and sampling was conducted within approximately 1 km of the sources. In Test 3, the influence of the tributary upon the neighborhood was studied by releasing SF_6 from a location approximately 2 km up the center of the tributary and releasing $CBrF_3$ from house 2. In Test 6, the valley drainage system was studied by releasing SF_6 and $CBrF_3$ from two locations further up the main Boise valley.

Concentration isopleths from the SF_6 tributary release in Test 3 are shown in Figure 2 for the period 2200-2230. Drainage flow down the tributary carried SF_6 out into the main valley where the tracer plume spread and moved down valley. High concentrations (normalized by the release rate in units of 10^{-6} s m^{-3}) decreased from near 100 within the tributary to 50 near the central park. During earlier periods beginning at 2030, the patterns were similar, although the concentrations increased from one period to the next throughout the test presumably because of increased atmospheric stability conditions.

For comparison to the tributary flow, isopleths of $CBrF_3$ tracer released from house 2 in the test neighborhood are shown in Figure 3. These isopleths are quite representative of the type of plumes observed in most of the neighborhood tracer releases. Extremely high normalized concentrations occurred immediately downwind of the source, and the plume spread relatively wide across the neighborhood. In some of the periods from test 3, the $CBrF_3$ plume appeared to have a bimodal distribution near the source with high concentrations immediately northwest and southwest of the house. Peak 30 min average concentrations decreased from 1600 just 100 m from the house

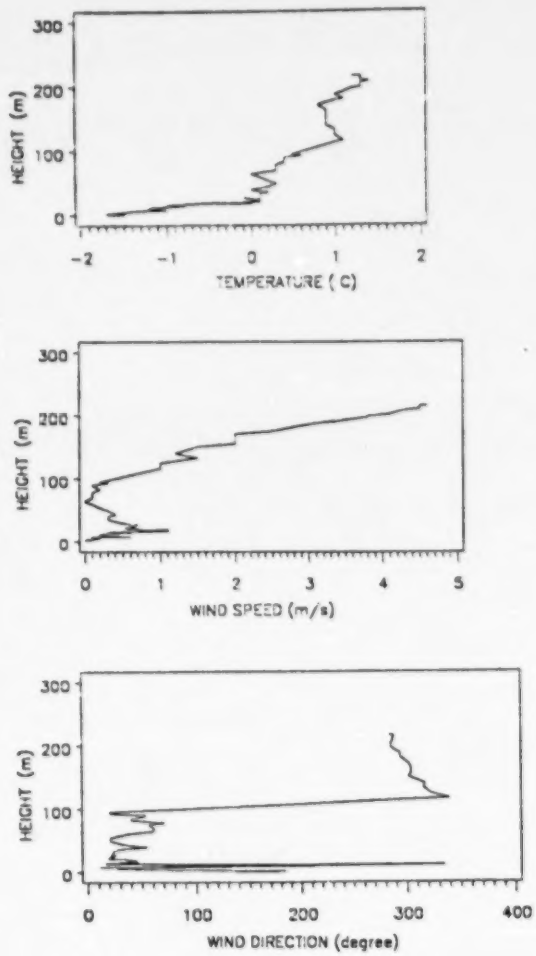

Figure 1. Typical vertical temperature and wind profiles (Test 2, 2056).

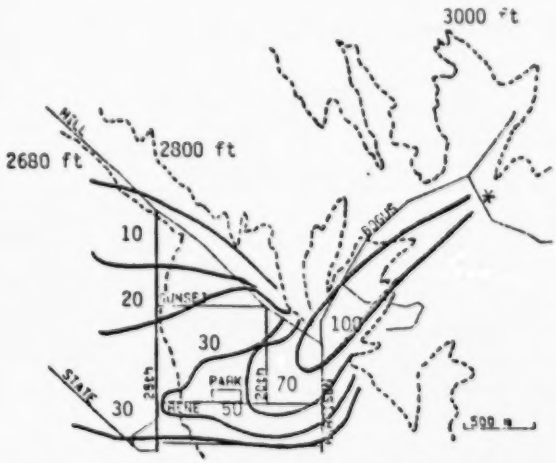

Figure 2. SF_6 isopleths (10^{-6} s m^{-3}) for Test 3 (2200-2230) for a release from the Bogus Basin tributary.

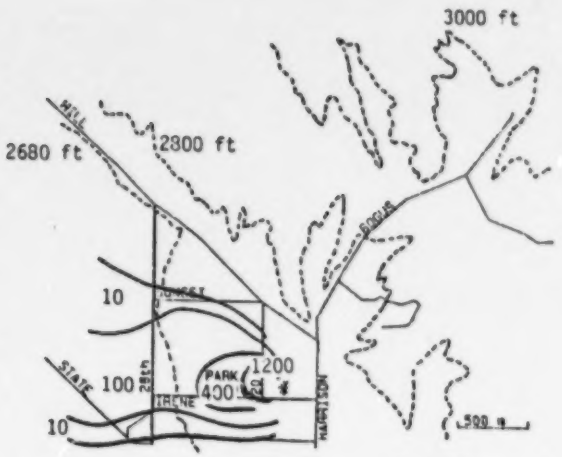

Figure 3. $CBrF_3$ isopleths (10^{-6} s m^{-3}) for Test 3 (2200-2230).

to approximately 100 at 1 km from the house.

Because the tributary contains a relatively dense suburban development, it represents a significant woodsmoke source upwind of the main test area. For that reason, it is of interest to estimate the relative impact of the remote tributary sources vs the local neighborhood sources. As a basis for comparison, the mean concentration from the highest ten concentrations of $CBrF_3$ can be compared to the mean SF_6 concentration over the same ten locations. In test 3, the ratio of the mean SF_6 concentration to the mean $CBrF_3$ concentration taken over the top ten $CBrF_3$ values varied from 6% in the first period to approximately 12% in the remaining three periods.

These results indicate that the air monitoring data obtained in the neighborhood park result from contributions of approximately 90% from nearby sources and 10% from far away sources up the tributary. However, this analysis does not include the contribution of other sources further upwind in the main Boise valley. It seems likely, though, that these other remote sources will contribute approximately the same or less than the tributary sources. The exact amount depends upon the amount of mixing which occurs between the tributary and main valley flows.

The tracer data can be used to estimate the amount of mixing which occurs between the tributary and main valley flows. If we assume that tracer is relatively well-mixed across the tributary flow, then the total air flow rate through the tributary is the inverse normalized concentration averaged across the tributary. Within the tributary, the estimated air flow rate is approximately 9000 m^3 s^{-1}, while just beyond the exit of the tributary, the estimated air flow rate is 15000 m^3 s^{-1}. This indicates that the tributary flow has entrained valley air of a volume equal to approximately 60% of the initial tributary flow.

Air flow across the neighborhood curves because of the drainage winds from the tributary. As a result, tracer plumes released from the different neighborhood houses traveled in slightly different directions across the test area. As shown in Figure 4 for the first period from test 2 (1900-1930), the SF_6 plume released from house 1 400 m directly south of the tributary exit was transported toward the southwest. At the same time as indicated in Figure 5, the $CBrF_3$ tracer plume released from house 2 170 m west of house 1 was carried toward the west.

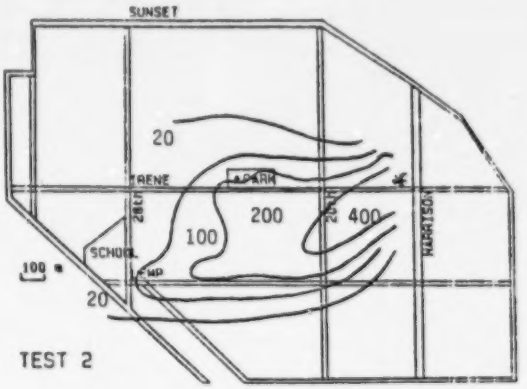

Figure 4. SF_6 isopleths (10^{-6} s m^{-3}) from Test 2 (1900-2000).

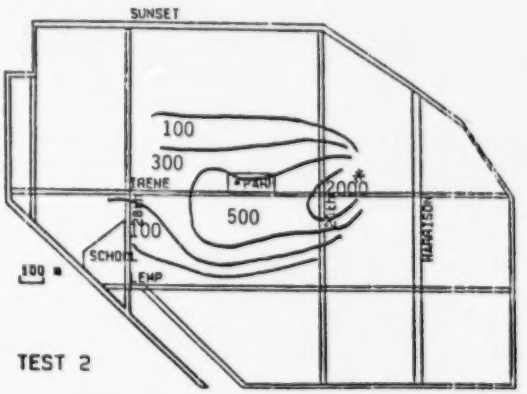

Figure 5. $CBrF_3$ isopleths (10^{-6} s m^{-3}) from Test 2 (1900-2000).

The relative impact of different houses, near and far away, can be estimated from the neighborhood tracer releases in the same manner as used above. The mean of the highest ten $CBrF_3$ concentrations can be compared to the mean of the SF_6 concentrations at the same receptors. For test 2 where drainage winds were relatively steady throughout the evening, the ratio of the SF_6 to the $CBrF_3$ means ranged from 15% to 31%. These are quite arbitrary results, however, since the relative contributions of emissions from any two houses will depend directly upon the specific source-receptor geometries and relative emission rates.

For the small scales of interest in this work, we can use the Gaussian plume equation to estimate the relative impact of any two sources. For simplicity we will assume the emission rates are equal, the source and receptor heights are zero, and the horizontal and vertical diffusion coefficients can be estimated as the product of the standard deviation of wind direction fluctuations and downwind distance ($\sigma_y = \sigma_\theta x$; $\sigma_z = \sigma_\phi x$). The ratio of concentrations from sources 1 and 2 then can be written:

$$C2/C1 = x_1^2/x_2^2 \exp[-.5(y_2/\sigma_y)^2]$$

where the receptor is along the centerline of source 1 (i.e. $y_1=0$). For this case, the relative impact of source 2 to source 1 depends only upon the respective downwind distances, the crosswind distance for source 2, and the horizontal diffusion coefficient for source 2.

The unknowns in this approach are the emission rates for the two sources and the horizontal diffusion coefficient. The tracer data can be used to estimate the horizontal diffusion coefficient from the mass distribution of tracer along crosswind sample lines at various downwind distances (Sackinger et al., 1982). The diffusion coefficients obtained in this fashion are graphed vs downwind distance for all the neighborhood scale tracer releases in Figure 6.

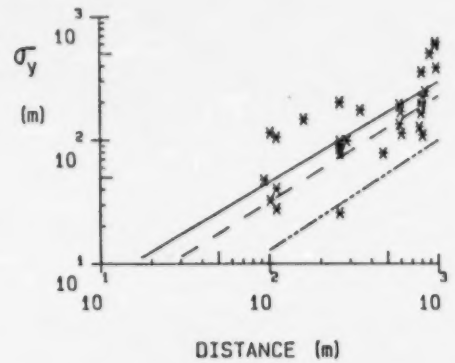

Figure 6. Horizontal diffusion coefficient vs downwind distance (* ——————) best-fit $\sigma_y = 1.11\ x^{.81}$; (--------) $\sigma_y = \sigma_\theta x/u$; (—·— ——·—) Pasquill-Gifford Class C.

The observed hourly averaged diffusion rate from these stable nighttime residential measurements follows a best-fit curve given by $\sigma y = 1.11x^{.81}$ with $r = 0.79$. For comparison, this residential diffusion rate is much larger than that predicted for rural class C (unstable) conditions as indicated by the lower dashed line in Figure 6. Given the significant size of the roughness elements in a residential neighborhood and the very light (< 1 m s^{-1}) winds observed in all of these tests, the large plume spread is not surprising. However, the observed diffusion rate is larger than comparable measurements for an urban area under neutral conditions (McElroy-Pooler curves) and it is slightly larger than we observed in our preliminary tracer studies in Pullman, WA.

Estimates of the horizontal diffusion rate from sonic anemometer measurements of σv ($\sigma y = \sigma v\ x/u$) are in reasonable agreement with the observed diffusion coefficients. The upper dashed line in Figure 6 is a best-fit line of the calculated diffusion coefficient vs distance. The mean absolute difference between the calculated and observed diffusion coefficients was ±55%. Given the extremely low wind speeds observed in these tests, the agreement between the observed and calculated values of σy is very good.

4. CONCLUSIONS

The results of the multiple tracer tests conducted during the EPA Integrated Air Cancer Program provide data for estimating the relative impact of various sources upon the central air quality monitoring site used in the study. Woodsmoke emissions from an upwind tributary to the main Boise valley are carried across the neighborhood, but the tracer data from one test indicate that the contribution of these upwind sources is approximately 10% of that from houses in the local neighborhood. For one house located approximately 200 m upwind of a second house, the tracer data show that emissions from the first house can contribute between 15% to 30% of the concentration caused by emissions from the downwind house averaged over the highest ten nearby receptors. A simple modeling analysis shows that this kind of relative impact depends directly upon the relative emissions rates, the difference in downwind distances, and the horizontal diffusion coefficient. For the very light wind, stable conditions which occurred during these tests, the hourly averaged diffusion rate was considerably larger than even unstable rural diffusion rates. However, estimates of plume diffusion from horizontal turbulence data were in reasonably good agreement with the measured plume diffusion rate.

Acknowledgements

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